I. Executive Summary

In order to address the current energy limitations of unmanned underwater vehicles (UUVs), this interprofessional project investigated the potential use of a fuel cell as a power source, replacing a conventional battery source as well as designing a UUV around this new power plant. A sodium borohydride fuel cell was selected for this specific underwater application as research has demonstrated its particular strengths. Using experimental data and theoretical analysis, the team has been able to design and produce a gold/platinum catalyst on a carbon substrate which will be used for further experiments. The team has also specified a complete submersible package including dimensions, control surfaces and material requirements.

II. Purpose and Objectives

Submarines have been in use since the 19th century. Submarines have been used mainly for military and deep sea surveillance and salvage. The first militaristic use of underwater vehicles occurred during the American Civil War in 1776. The Turtle, an egg shaped man powered device designed by David Bushnell, was used in an attempt to sabotage the British warship HMS Eagle in New York harbor. Unfortunately, the attempt failed and it was not until World War I would submarines be utilized as weapons of war. German U-boats changed the warfare in the Atlantic and would forever change the nature of warfare on the high seas. Submarines have enabled countries to spy on each other from beneath the waves and in the event of a nuclear war are able to annihilate the attacking countries. Submarines also pose a very deadly threat to shipping, battleships, and aircraft. However, conventional submarines are limited by their requirement to have people on board. People require oxygen and space, both of which are very costly aspects of submarine design and also limits the places the submarine can go by shear nature of its physical size. This presents a need for unmanned submersibles. Another problematic area of submarine design is propulsion. Within the realm of propulsion issues, fuel is probably the biggest problem. Nuclear submarines are very large and require a lot of very close maintenance while gas powered submarines are very resource intensive. Batteries and fuel cells pose better alternatives.

Fuel cells are electrochemical devices capable of producing electricity at a rate that is two or three times as efficient as compared to an internal combustion engine. In the simplest form a fuel cell combines hydrogen and oxygen in order to produce water, heat, and an electric current. This type of fuel cell is known as a Polymer Electrolyte Membrane fuel cell. Nevertheless there are four additional types of fuel cells. Alkaline, phosphoric acid, molten carbonate, and solid oxide fuel cells are also currently being researched. Each of these fuel cells has unique advantages and disadvantages which can be either beneficial or detrimental to the design of a UUV. For instance in 1998 Chicago incorporated a hydrogen powered fuel cell into their city busses. A similar technology could be examined for use in the UUV.

This IPRO aims to help alleviate these design issues by removing the human element from and thusly creating an unmanned underwater vehicle (UUV) that provides for a safer, more efficient way to accomplish underwater tasks. This efficiency can be further enhanced by the implementation of a fuel cell as the power source. By the end of this semester, a prototype fuel cell for underwater applications will be developed along with a design of an unmanned underwater vehicle for it to work with. The design of these two parts will be conducted with a United States naval application in mind, though it is not the sole guiding light of the project.

A UUV would be highly desirable by the US Navy because of its ability to operate in conditions that would normally be impossible for manned submarines. Therefore, if a stealthy and long range UUV can be developed it will be very appealing to the Navy and could be used for a wide variety of missions from reconnaissance to sabotage.

III. Organization and Approach

Addressing the problem

The IPRO 349 team researched currently existing fuel cell technologies that can be used for the generation of electrical energy to propel underwater unmanned vehicles also known as UUV's. These kinds of vehicles are of special interest for military use and underwater exploration. There are two main challenges in this project:

- The field of fuel cells is quite developed theoretically but hasn't been perfected practically because of the sophisticated nature of the technology, its components and the materials needed to build those components.
- The potential use of the UUV in military applications is a challenge to perfect the system in every possible way so that it cannot be detected and it can accomplish its task.

So, in order to perform the tasks efficiently, the IPRO 349 team, which is made of 24 members, split into 3 sub-teams with a team leader for each team.

The Fuel Cell Team

Led by Chris Wolcott, the main objective of this team was to look into the details of the fuel cell itself which includes:

- The types of fuel to be used.
- Reactions/Electrochemistry.
- Catalyst to be used.
- Membranes to be used.
- Amount of energy (electrical/thermal) produced by the fuel cell.
- Efficiency of the fuel cell compared to the next best alternative.

The fuel cell team will be responsible selecting and designing the fuel cell power system for the UUV. This will include two main phases. The first phase will be working with the research team to review existing fuel cell technologies and selecting what fuel cell system to use. The second phase will involve developing a thorough design of the fuel cell system based on specifications found by the research team. Key challenges for this team will be communicating with the research team to select the best fuel cell system and working out the specifics of a detailed design for use in an UUV.

The Propulsion Team

Led by Marcus Choy, this team mainly dealt with the following tasks:

- Conversion of the electricity produced by the fuel cell to its useable form (AC/DC).
- Type of the propulsion system to be used.
- Stability and buoyancy of the UUV.
- Calculation of the weight of the overall UUV including its components.

The propulsion team selected and designed the best propulsion method to provide optimal range and sufficient thrust to meet design criteria. The selected type of propulsion system had a low thermal signature and is low in noise due to considerations of naval applications. The DC current from the fuel cell will need to be converted to AC current depending on the type of current needed. Types of propulsion systems to consider are: a shark based propeller, screw-drive, MIT “turtle” and jet. The team also determined a range and efficiency of the system. The main challenges for this sub-team are similar to those for the fuel cell team. They needed to communicate effectively with the research and fuel cell teams to determine the exact demands placed on the propulsion system, as well as work out the technical aspects of a detailed design.

The Research Team

Led by Brian Olson, this team conducted research in order to provide the team with the most up-to-date information on various aspects of this project to the other two sub-teams.

Their primary tasks were to find:

- Same/similar current models if any.
- Available alternative options.
- Specifications – power requirement, available space, range, payloads, etc.
- Expected cost of the UUV.
- Expectations of other potential consumers.

The research team was in charge of gathering information from various sources and relaying it to other teams for consideration. They were chiefly responsible for researching information related to the specifications of existing UUVs, such as size, power requirements, and propulsion systems. They also worked with the fuel cell team to research different types of fuel cells. The research team also worked with the propulsion team to look at different methods of propulsion for underwater vehicles. Finding and conveying all of this information to the other sub-teams was the principle challenge for this sub-team. Because of the immense amount of information available it was necessary for the team to be able to concisely convey their findings in order for the other sub-teams to properly utilize their work. After completing the initial phase, the research group was dissolved into the other two groups such that the people involved in the various aspects of research would then be able to assist in the design process.

IV. Analysis and Findings

The Fuel Cell Team

The fuel cell sub team spent the first part of the semester performing a thorough literature survey to explore different fuel cell configurations which could be used. The team looked for a fuel cell system which used a fuel and oxidant which produced no gaseous products, had density similar to water, and was easy to handle. With these parameters in mind the team decided to use a direct borohydride fuel cell (DBFC) for the system based primarily on its high power density, its lack of gaseous reaction products, and its ability to use aqueous fuel and oxidant helping to maintain neutral buoyancy. The team selected to use sodium borohydride as the fuel and hydrogen peroxide as the oxidant. Each of these chemicals can be handled very easily and are nowhere near as hazardous as many alternatives [FC1].

After selecting the fuel and oxidant more research was performed to determine the best catalysts and membrane to use. Gold supported on carbon was selected for use as the oxidant catalyst. Despite not performing as well as some other catalysts like platinum, gold was seen to greatly reduce the amount of oxidant undergoing direct reduction and producing oxygen gas [FC2]. For the fuel catalyst 97 wt% gold, 3 wt% platinum on carbon was chosen. This catalyst had been shown to limit a side reaction producing hydrogen gas [FC3]. For the membrane Nafion™-961 was selected. It was shown to have similar performance to other cation exchange membranes in a DBFC, but also helped mitigate some problems caused sodium ion transport across the membrane [FC4] which will be discussed in more detail later.

Having fully specified the materials to be used in our fuel cell, research was performed to find the best catalyst loading, fuel cell temperature, and fuel and oxidant concentration. Because much of this information had been discussed in papers we had already found this did not take long. A summary table of what was found is shown below.

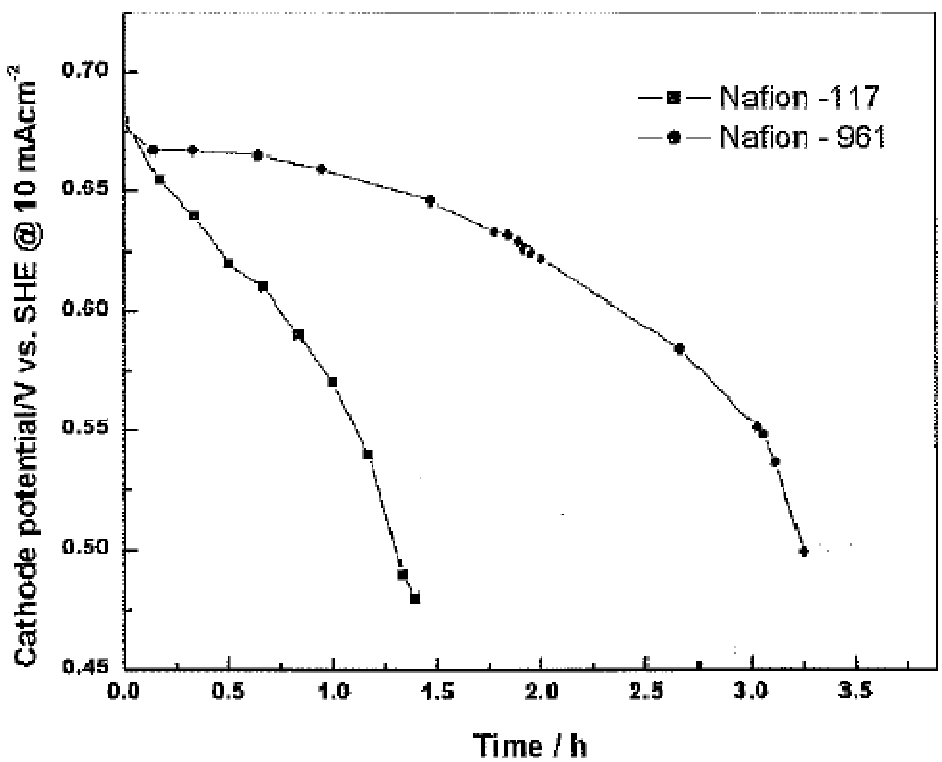
Temperature	25°C
Catholyte Composition	2M H2O2, 1.5M H_2SO_4
Cathode Catalyst Loading	60 wt% and 2mg/cm^2
Anolyte Composition	8 wt% NaBH4, 11wt% NaOH

Anode Catalyst Loading	60 wt% and 2mg/cm^2

[FC5]

With all of this information on hand the fuel cell team split into three smaller groups to work for the remainder of the semester. One group focused on looking at problems caused by using a cation exchange membrane in the DBFC. One group attempted to build a prototype fuel cell, and the remainder of the sub team members worked on producing a detailed design.

The sodium problem group spent the last few weeks of the semester looking at problems caused by sodium transport across the membrane. The use of a cation exchange membrane resulted in two major problems. One is that because sodium is transported across the membrane and not back, if a recycle stream is used a sodium imbalance will eventually build up across the membrane, hindering fuel cell performance. The other major problem is that due to Nafion™ being designed for small ion transport, large ions like sodium can block the pores of the membrane, causing the fuel cell performance to decrease as shown in the following figure.



[FC4]

As can be seen in the figure Nafion 961 shows dramatically better performance than Nafion 117, but does not totally solve the problem. The sodium problem team was responsible for looking into potential solutions to these two problems, as well as trying to find how dramatically they impact fuel cell performance. This is an area of active research, so no simple solutions are available. Additionally because a recycle stream was going to be used, an imbalance of sodium would occur across the membrane hindering ion transport.

Research showed found that with the capacitative deionization (CDI) of water, where the charged ion is pulled into an electric double layer (EDL), could potentially be a solution to the sodium imbalance problems. It would be a way of pulling the Na out of the cathode and then holding it in the EDL until the vehicle came back, at which point it could be cleaned and removed. Looking at the problems with membrane clogging, one potential solution would be to use a new type of Nafion membrane, which is better suited to large ion transport called Nafion-XL. The best solution to these problems with sodium would be to use an anion exchange membrane. This would cause a different species to move across the membrane, eliminating the sodium problems. Unfortunately anion exchange membranes are still being researched and currently have many defects, which is why one was not selected to be used.

The prototyping team developed a fuel cell in the lab to understand more about the intricacies of sodium borohydride fuel cells. They attempted to recreate the results that were used to design the fuel cell based off of the literature survey. First, the prototype team needed to create a list of materials needed to build the fuel cell. This included items such as sodium borohydride, potassium hydroxide, gold precursor and pumps. Many of the other items were provided by our professor's lab such as membranes, catalyst ink, and hydrogen peroxide. Once the items arrived, schedules were set up for the prototyping team to meet in the lab.

Once in the lab, the experiments that needed to take place to create a fuel cell were prepared. First, catalyst needed to be produced. The ideal catalysts that were chosen were Gold and Gold/Platinum mix for the anode and cathode sides respectively. These catalysts are not widely produced and, therefore, a gold precursor needed to be found and used to make gold nanoparticles. Once the nanoparticles are formed, they needed to be put on carbon to make the electrodes. In the lab, the first attempt to make the catalyst did not produce any gold nanoparticles that correctly adhered to the carbon. The second attempt to produce the nanoparticles garnered using a different experimental method garnered the following results. Figure 2 shows various x-ray diffraction data from catalyst that contained 100% gold nanoparticles, 100% platinum nanoparticles and varying amounts of gold with platinum. The highest peaks of both the gold and the platinum, in Figure 2, are so close to one another that the determination of our catalyst having mostly gold with some platinum was determined by the small amount of "noise" that can be seen (Figure 1).

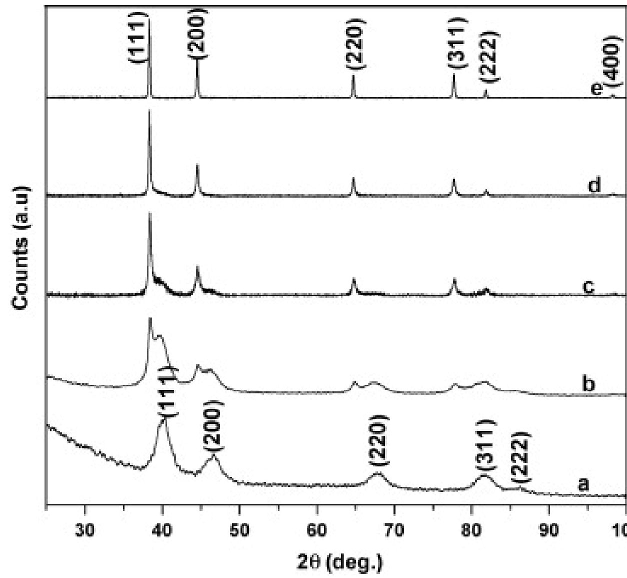


Figure 1: XRD data from literature; a is 100% Pt and e is 100% Au, b-d is mixtures of Au/Pt

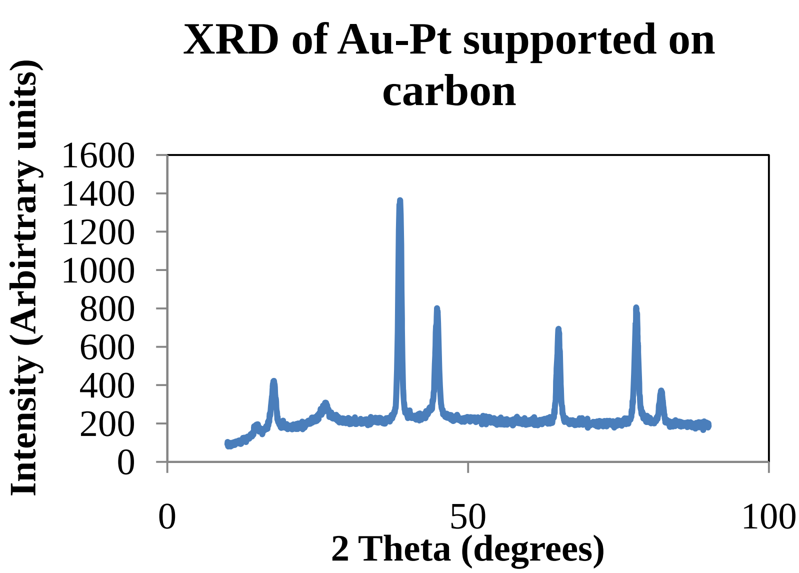


Figure 2: Lab results for second attempt at producing catalyst. This is a mixture of Au and Pt.

Due to time and material constraints, the gold and platinum mixed catalyst was used on both the anode and cathode side. Not enough gold was present to make a pure gold catalyst. Catalyst ink was formed and this substance was painted onto 5 cm^2 pieces of carbon creating the electrode. The membrane electrode assembly was made by adhering the electrode to the Nafion membrane.   The next step was to make the fuel and oxidant for the cell. A 0.1mM solution of hydrogen peroxide in water was made along with an 11% by weight solution of sodium borohydride.   With all of the elements of the cell made, the pumps were tested and flow rates determined. The pumps were tested for calibration purposes using water. It was determined that on the slow setting, the following results were obtained.

Speed Level	Flow Rate
1.5	138.5 mL/min
2	230.7 mL/min
3	409.8 mL/min

The fuel cell with these parameters produced results far below those expected. Changes were made to the fuel cell to increase performance. The membrane electrode assembly was created using a thicker Nafion 117 membrane instead of the Nafion 112 membrane. Also, the concentration of the sodium borohydride solution was decreased from 11% by weight to 4% by weight. It was seen that with higher flow rates a higher voltage and power density was garnered. The flow rate calculations for sodium borohydride and hydrogen peroxide on the "fast" pump settings are summarized below.

Speed Setting	Hydrogen Peroxide	Sodium Borohydride
3	28.8 mL/s	31.8 mL/s
4	33.95 mL/s	35.9 mL/s
5	35.8	38.4 mL/s

By using these pump speeds and the newly created membrane electrode assembly with the thicker Nafion 117 membrane and the lower concentration solution of sodium borohydride, we achieved results similar to those found in the literature survey. From the graph shown below, the power density and voltage results from our fuel cell are shown. It can be extrapolated that the fuel cell voltage, while still not as high as that found in the literature survey, was better than the previous test run. The power density, however, was still significantly lower than the results found in the literature survey.

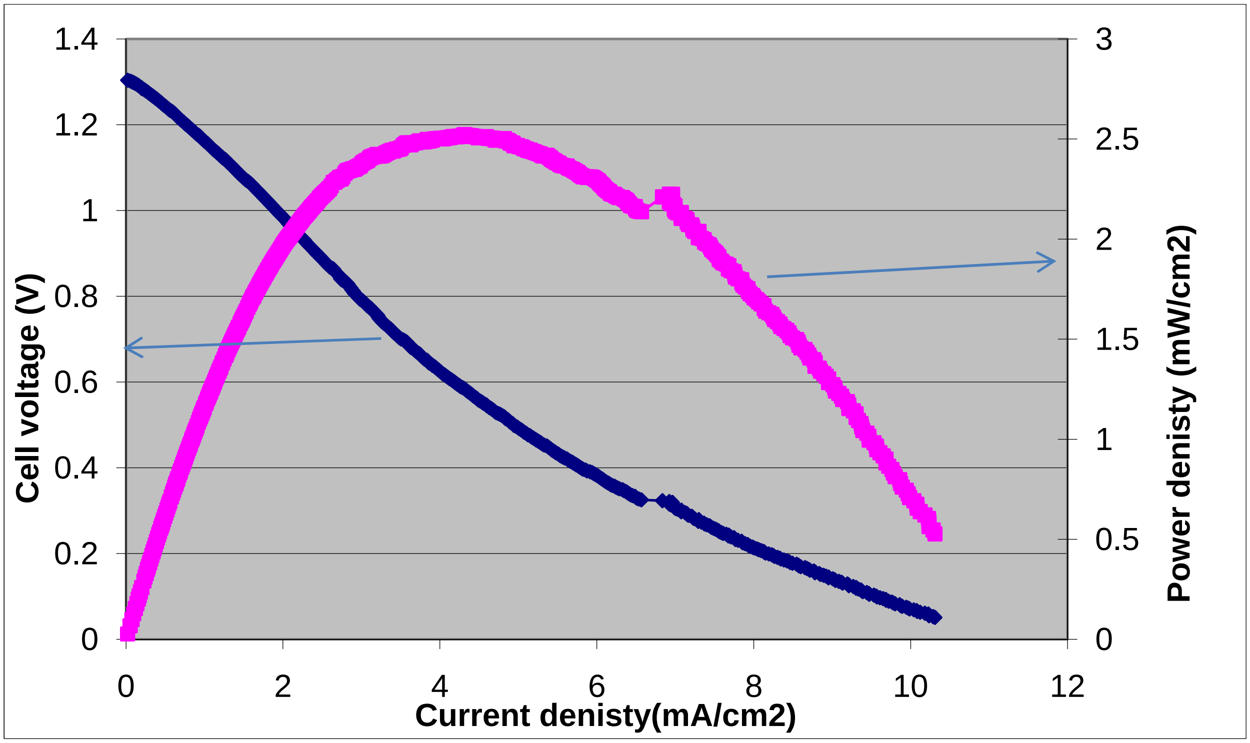
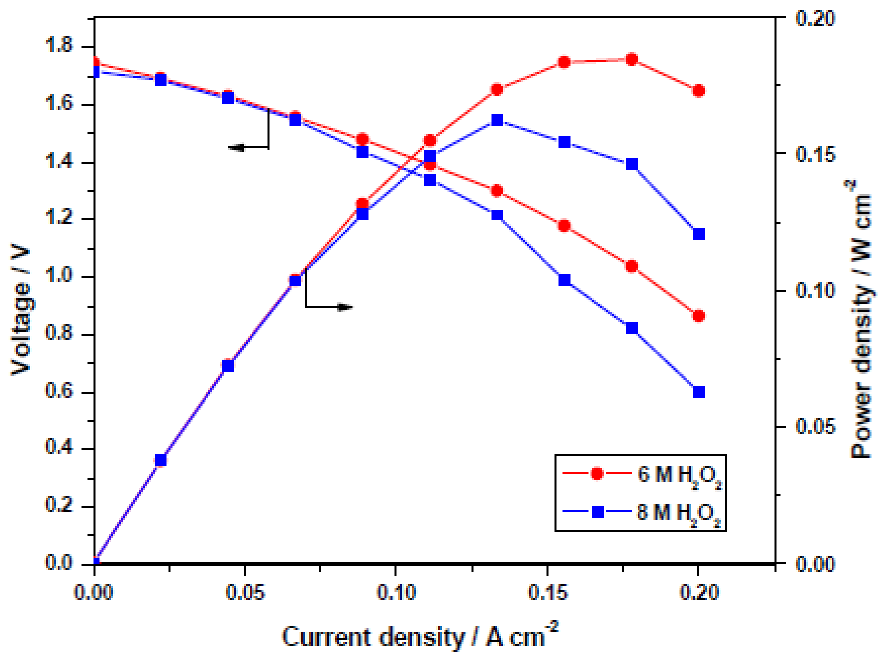


Figure 3: Final polarization data from experimental results

The design group worked on getting rough numbers for the size of the fuel cell system. Ideally the group planned to develop two designs, one based on fuel cell performance from literature and one based on experimental results from the prototype group. However because of the limited amount of time only the literature design was completed.

The literature based design was not an identical system to the one we had planned on using, but it was as similar as could be found [FC5]. Based on the estimated power requirements from the Propulsion sub team we designed a 2kW system using the peak performance shown in the following figure.



[FC6]

From this polarization data an operating voltage was selected for the fuel cell to put out 24V required for the motor. The operating current of 0.12A/cm2 is drawn from our system. Because the diameter of 1 cell stack is 31cm (cross sectional area of 1 cell stack is 755cm^2, the expected current is 90.57A (C/s).

(1) Q=n*NA*e

According to the above equation (1), the number of moles of electrons can be calculated as Q, NA, and e stand for flowing charge, Avogadro's Number, and charge on an electron, respectively. Then, the calculated number of moles was divided by 8, because 8 hydrogen ions are given from the reaction. This yields a molar flow rate of 1.17E-4 moles of NaBH4 per second and it is converted to flow rate of fuel with some conversion factors, including the molecular weight of NaBH4, as 0.0038 Liters of NaBH4 per minute. Density of water for the fuel, 90% efficiency, 30days duration, and 60 cell stacks were assumed, and approximately 97.6 Liters of fuel tank size were determined as necessary for 1 day of operation.

For the estimation of the oxidant tank size, total stoichiometry was used. 4 moles of H2O2 are required for 1 mole of NaBH4, or 4.77E-4 moles H2O2 per second. Using the molarity of the oxidant (6M), the flow rate of oxidant was calculated as 0.084L/min, requiring an oxidant tank size of 120.4L.

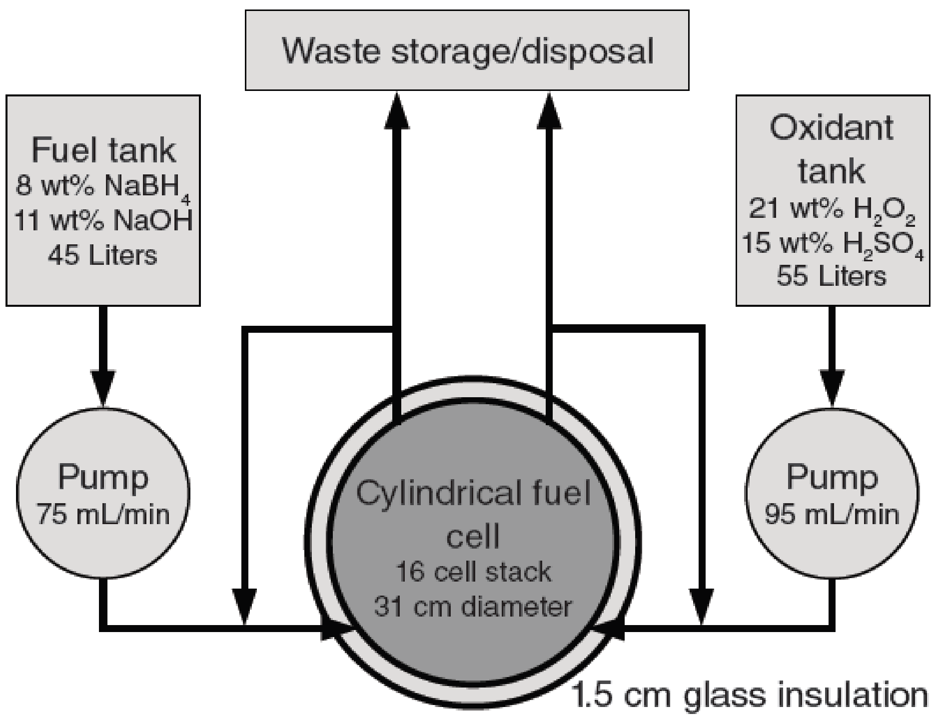
After calculating the size required 1 day of fuel, it was determined that the volume of UUV doesn't have enough space. Assuming that half of the UUV (125L) would contain fuel and oxidant tanks, the tanks were resized proportionately and the endurance of the

UUV calculated as the following: 45L for the fuel tank and 55L for the oxidant tank which may operate 11 hours or approximately 70 kilometers at full speed. The results are summarized in the figure below

From this the fuel cell and the fuel and oxidant flow rates and tanks were sized as specified in the following figure.

Fuel Cell Design Results

Number of cells	16
Cell operating voltage	1.5 V
Fuel cell length	29 cm
Fuel cell volume	23 L
Cell power output	2 kW
Cell voltage	24 V
Range	70 km



Additionally based on an estimated efficiency of 50% for the fuel cell, it was found that the fuel cell would need insulation to maintain its operating temperature. The fuel cell is initially at 25°C. Air, which is present inside the UUV, is a bad conductor of heat but convection can occur in air. So, assuming that the air is well mixed, the inner wall temperature of the fuel cell reaches 25°C after a certain amount of time. Steel conducts heat very well and has a thermal conductivity coefficient (k_{steel}) of 43 W/mK. Outside the UUV, heat is lost mainly by forced convection because the UUV is moving with some velocity (v = 2 m/s). This heat transfer mechanism can be shown by the following resistance diagram:

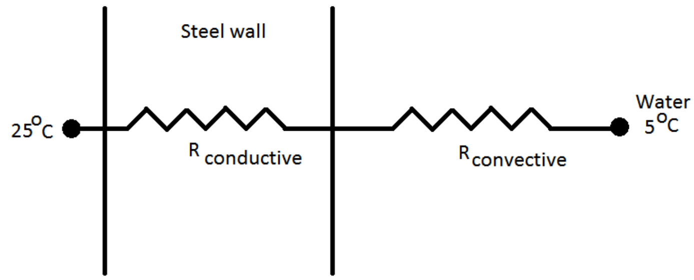


Figure 4 Heat transfer diagram.

The conductive resistance is written as:

$$R_{cond} = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi k_{steel} L} \quad (1)$$

Substituting the values of r_2, r_1, k_{steel} and L (length of the UUV) in equation 1. gives

R_{cond} = 2.0518 X 10^{-4} K/W.

The convective resistance is written as:

$$R_{conv} = \frac{1}{hA} \quad (2)$$

In Eqn. 2, 'h' is the convective heat transfer coefficient and 'A' is the outer surface area of the UUV. The value of 'h' has to be calculated by using various dimensionless numbers. The Reynolds number for water at film temperature (temperature between the outer wall of the fuel cell and the water layer very close to the outer wall ≈ 15°C) is calculated by using the following formula:

$$Re = \frac{Lv\rho}{\mu} \quad (3)$$

L is the length of the convective heat transfer surface (assumed to be the length of the UUV), v is the velocity of the UUV, ρ is the density of water at the film temperature and μ is the viscosity of water at the film temperature. The values of these parameters are as follows:

L = 3.1 m

v = 2m/s

ρ = 998 kg/m^3

μ = 1.131 X 10^{-3} kg/m.s

Equation 3, gives Re = 5.4709 X 10^{6}

At the given Reynolds number, the equation for Nusselt number (another dimensionless quantity) is:

$$Nu = 0.0366\,\sqrt{Re}\,Pr^{\frac{1}{3}} \qquad (4)$$

Pr is the Prandtl number which is equal to 8.07 for water at 15°C.

Solving Eq. 4 gives: Nu = 171.7126

Finally,

$$h = \frac{Nu}{kL} \qquad (5)$$

The value of 'h' obtained from Eqn. 5 is 94.1386 W/m^{2}K

Outer surface area of the UUV (A) = $2\pi r_2 L$ = 3.7008 m^2

Thus, from Equation 2. R_{conv} = 0.0029 W/K

The total resistance is the sum of the conductive and convective resistances.

$$R = R_{cond} + R_{conv} \qquad (6)$$

The rate of heat transfer is given by:

$$q = \frac{T_{inner\ wall} - T_{water}}{R} \qquad (7)$$

Solving Equations 6 and 7 gives:

Rate of heat transfer, q = 6.5029 kW

Thus more heat will be lost than the amount of heat produced by the fuel cell. In order to maintain the operating temperature of the fuel cell at 25°C, we can either heat the fuel cell to provide 4.5029 kWof extra heat that is being lost or we can allow only 2kW of heat to transfer to the outside water by insulating the fuel cell. Heating the fuel cell requires electric power which is a very limited resource in this project. Thus, we decided to insulate the fuel cell.

A solid material with a low conductive heat transfer coefficient should be used for this purpose. This will also obstruct the heat flow due to convection. So, the main objective is to find a suitable material and its thickness.

Reverse calculations are done to calculate the thickness of the material to be used. Using equations 6 and 7, and q = 2 kW, the temperature of the inner wall is calculated to be 11.15°C. Thus the outer surface of the insulating material should also be roughly at a temperature of 11.5°C assuming that the water properties do not change greatly at a new film temperature of about 8°C ensuring that the convective heat transfer coefficient also does not change greatly.

The inner surface temperature of the insulating material is about 25°C and the outer surface temperature of the material has to be about 11.5°C. Only 2 kW of heat must be allowed to transfer through the material. Some of the suitable insulating materials are as follows:

Table 5 Different insulating materials and their properties

Name of the material	Thermal conductivity, k (W/mK)	Density
Asphalt	0.75	1995.8 kg/m³
Mica	0.71	2882 kg/m³
Glass	1.05	2400 kg/m³
Gypsum plaster	0.48	2308 kg/m³
Carbon	1.7	2100 kg/m³

The resistance of the material for heat transfer is given by:

$$R_{cond} = \frac{T_{inner\ surface} - T_{outer\ surface}}{q} = \frac{25 - 11.5}{2000} = 0.0067\ K/W \quad (8)$$

The ratio of the radius of the outer surface (r_o) to the radius of the inner surface (r_i) is given by a modified form of Eqn. 1:

$$\varepsilon = \frac{r_o}{r_i} = e^{2\pi R_{cond} k_{material} L} \quad (9)$$

Table 6 Different insulating materials and the ratio of their surface radii (outer to inner)

Name of the material	Thermal conductivity, k (W/mK)	$\varepsilon = r_o/r_i$
Asphalt	0.75	1.1028
Mica	0.71	1.0971
Glass	1.05	1.1469
Gypsum plaster	0.48	1.0646
Carbon	1.7	1.2484

The thickness of the materials can be calculated as follows:

$$t = r_o - r_i = \varepsilon r_i - r_i = r_i(\varepsilon - 1) \quad (10)$$

The following table lists the thickness of the materials to be used:

Table 7 Different insulating materials, their thermal conductivities and thickness.

Name of the material	Thermal conductivity, k (W/mK)	t (mm)
Asphalt	0.75	10.17
Mica	0.71	9.61
Glass	1.05	14.54
Gypsum plaster	0.48	6.39
Carbon	1.7	24.59

Looking at Table 7, we would suggest using glass as the insulating material because of the following reasons:

- Cheap and clean to work with.
- Transparent, thus makes the enclosed things (fuel cell, wiring, etc) visible for inspection.
- Density is in the middle range of all the materials listed.
- At a thickness of 14.54 mm, it will be quite rigid and strong, so won't break easily unlike plasters made out of powdered materials.

The environmental effects of the chemicals in our system were also investigated. Hydrogen peroxide is environmentally benign in water and causes no major problems. It will decrease in concentration quick enough to not be an issue. Sodium borohydride has more of an environmental impact, but is in low enough concentration that it is unlikely to cause much harm. Like hydrogen peroxide it also breaks down quickly in water. The sodium borate is quite benign in water, and has no strong environmental impact. The sodium hydroxide and sulfuric acid are both chemicals which occur in nature and will not cause any environmental harm.

A summary of the specifics of the fuel cell system based on literature performance is shown in the figure below.

Fuel Cell Design Team Results

Fuel Cell Dimensions	31cm Diameter x 29cm Length
Fuel Cell Voltage	24V
Fuel Cell Power Output	2kW
Fuel Flow rate	0.075 L/min
Oxidant Flow rate	0.095 L/min
Total Fuel Pump Power Needs	<10 W
Fuel Tank Size	45 L
Oxidant Tank Size	55 L
Fuel Tank Material	Polyethylene bag in Aluminium
Oxidant Tank Material	Low Carbon Stainless Steel
Run Time at Max Power	11 hours
Max Range*	70 km
Submarine Heat Loss Estimation	7kW
Fuel Cell Heat Output	2kW
Insulating Material	Glass
Thickness of Insulation	1.5 cm

*Assumes running at max power

The Propulsion Team

During the first half of the semester, the propulsion sub team was placed in charge of several tasks. These tasks are the overall submarine design, the design of the propulsion system, and the design of the control systems. It is important to note here that the ocean water is assumed to be and the properties of ocean water are taken at an average ocean depth of 12,430 feet (3790 meters).

The overall submarine design involved the selection of a UUV class for which the design would be based off of. There are four classes of UUV's defined in the Navy's Masterplan for UUVs, the man portable, the light (medium) weight, the heavy weight, and the large vehicle class submarines. As the various names of the submarines imply, the submarines each have a different size, weight, payload, and operational requirements. During one of the earlier class meetings, it was decided that the class wanted to design for the light weight vehicle class. The UUV Masterplan specifies that the submarine have a total displacement of five hundred pounds and suggests that the submarine have a diameter of about 12.75 inches (32.385 cm). Once the vehicle class was determined, the propulsion group then began to generate concepts for both a practical and theoretical submarine.

The goal of the theoretical team was to generate concepts and ideas for a submarine with non canonical features (i.e. non cylindrical cross section and state of the art propulsion systems). This was done simultaneously while the practical group approached the problem using conventional designs. In the end it was decided that pursuing a practical design was a better use of time due to the fact that the main goal of the IPRO is to utilize fuel cells in order to power the submarine and it is easier to design the fuel cell given hard specifications.

By the end of the semester the UUV was designed using a conventional tear drop shape due to the fact that it is the ideal aerodynamic shape with the least amount of drag. The UUV had an overall length of 3.48 m, an overall diameter of 0.31 m, and was to be made of titanium. See engineering drawing in Appendix ##. Titanium, steel, and aluminum were considered in order to create the UUV. Eventually it was determined that the corrosion resistance characteristics of titanium and the high strength to weight ratio was the ideal material to construct the UUV out of. Furthermore, using by modeling the submarine as a cylindrical pressure vessel, the thickness of the UUV was determined to be 2.7 mm and the surface area of the UUV was 3.57 m^2. In order to determine the thickness of the UUV is was first necessary to calculate the operating pressure of the UUV. In order to do this, the average depth at which modern submarines operate at is assumed to be 730 m. Then using equation 11 below the operating pressure is determined to be 7.34 Mpa.

$$P_{max} = \rho g h \tag{11}$$

ρ = 1025 kg / m^3
g = 9.81 m/s^2
h = depth = 730 m
P_{max}= Pressure at depth

This pressure is assumed to be the same as the pressure inside of the cylindrical pressure vessel. Due to the nature of pressure vessels, it is a well known fact that the hoop stress will exceed the yield strength of the material before the axial stress will. Therefore to calculate the thickness of the UUV, the formula for the hoop stress (shown below) is used.

$$\sigma_{hoop} = \frac{P_{max} r}{t} \quad (12)$$

σ_{hoop}=Hoop Stress
r=Radius of Pressure Vessel
t=Thickness

The mass and volume budget for the UUV was also determined during the semester. Figures 8 and 9 show the final mass and volume budgets. Note that these budgets were estimated based upon the design requirements that the UUV needed to be powered by fuel cells and needed to carry a payload.

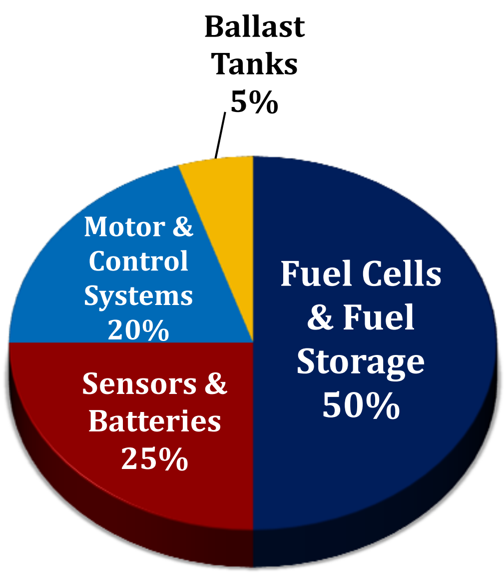


Figure 8: Volume budgeting in UUV

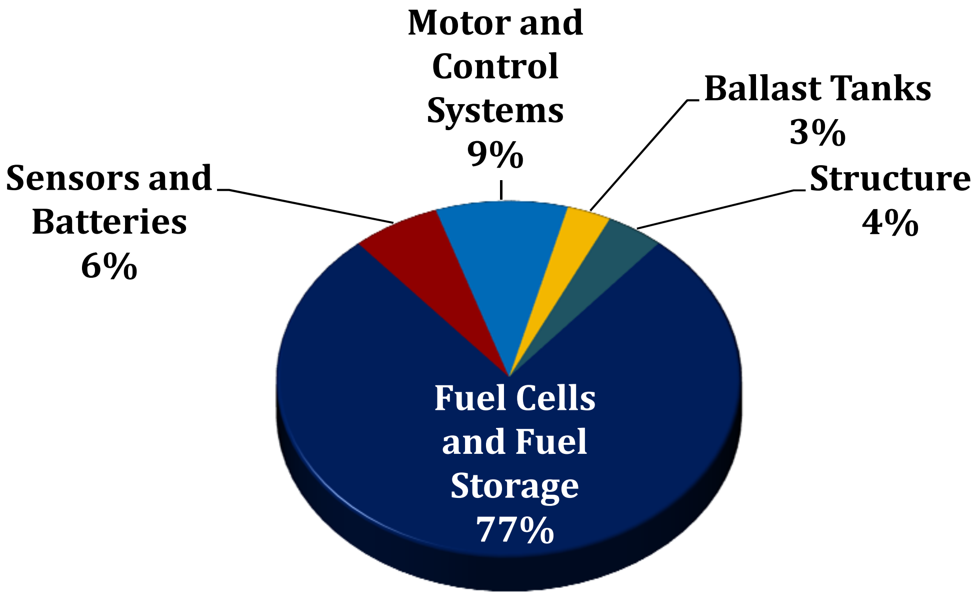


Figure 9: Mass budgeting in UUV

The second task is to determine the power requirements for a motor needed to propel the light weight submarine at the operational depth. In order to do this several assumptions were made. The assumptions are listed below.

1. UUV is moving at some constant velocity V.
2. The UUV is subjected to steady and incompressible fluid flow
3. The density of sea water is assumed to be constant at the operating depth
4. The UUV is traveling through still water. That is the free stream velocity of the water is zero ft/s (0 m/s).
5. The UUV is operating at a constant depth and therefore the change in potential energy of the submarine is negligible.
6. All mechanical and electrical components are ideal so there is no loss of efficiency.

From the first assumption, it is obvious that in order for the UUV to move at a constant velocity, the thrust provided by the motor needs to be equivalent to the drag force acting on the UUV. Where the drag force is given by equation 13 below.

$$F_D = \frac{1}{2}\rho V^2 C_D A \tag{13}$$

F_D=Drag Force
P=Density at operating Depth
V=Operating velocity
C_D=Coefficient of Drag
A=Cross Sectional Area of the UUV

Using this equation the power required to overcome the body and pressure drag acting on the UUV is calculated. Note in order to obtain a coefficient of drag, William Dziedzic helped to perform a first iteration computational fluid dynamic (CFD) analysis on the UUV. Note that in the CFD analysis of the UUV, it was assumed to be moving through the water at a cruising speed of 1m/s, yielding a coefficient of drag of 0.33. Microsoft Excel was then used in order to create a graph of the power in figure 10.

Also it was found it was found that the fuel cell team would only be able to provide 2 kW of power. Thus an optimum max cruising speed of 1.5 m/s or 5.4 km/hr was determined. Furthermore, the fuel cell team informed us that they would be able to provide 24 V of DC current. This gave us specifications to search for a commercially available motor that could be used in order to propel our UUV through the water. In the motor selection process, various motors were examined. We immediately eliminated AC motors due to the fact that we would need an inverter in order to be able to use an AC motor, which would lower the amount of mass and volume available for other components within the UUV. Upon further investigation, brushless DC motors were eliminated based on the fact that they were not powerful enough to power our UUV. Thus DC motors were selected as a potential propulsion system. Eventually, the Perm Motor PMG-132 from Electric Motorsport was selected. See table ## for motor specifications.

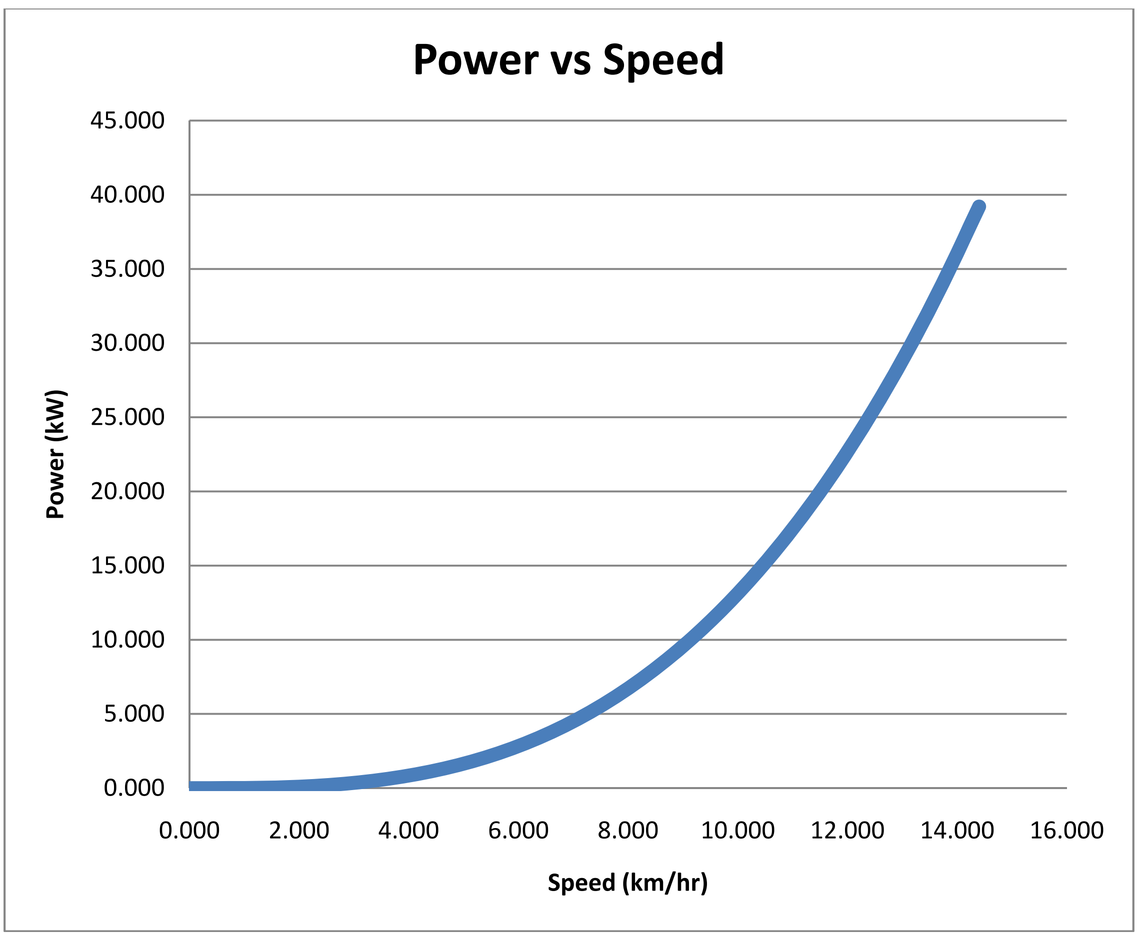


Figure 10: Power vs speed graph

Dimensions	
Body Length	120 mm
Body Diameter	222 mm
Shaft Length	43 mm
Shaft Diameter	19 mm

Specifications PMG 132 24V	
Voltage	24 V
Current	110 A
Power	2.2 kW
Speed	1080 rpm
Torque	20.5 N-m

The mechanical team also examined several other tasks during the semester but was unable to complete them due to time constraints. The mechanical team also examined possible ballast tanks, control of the UUV, and the analysis necessary in order to size and place the propeller.

Two ballast systems were examined. One system calls for fixed weights to be attached to the UUV, which would be jettisoned when the UUV needed to surface. However, this is an irreversible process and once the UUV surfaces it cannot submerge again. Another system that was examined by our group was the use of a ballast system. This system would consist of a valve to let a small amount of water in to a separate sealed compartment that holds the water. This causes the submarine to dive. Then when the submarine needs to surface, the water is pumped out of the submarine using a pump.

Additionally, the mechanical team was in charge of examining the control system of the overall UUV. In order to size the control surfaces area ratios were used. Furthermore, two methods of controlling the UUV were generated. One method involved the UUV following a preprogrammed mission, carrying out that mission and returning to the starting point in order to be picked up by its mother submarine. The second method involved the remote control of the UUV by a human operator. Unfortunately, the mechanical team was shorthanded and could not perform a more in depth analysis of the control system.

Lastly the mechanical team examined the size and placement of the propeller of the UUV. Note, unfortunately, only an investigation of the equations necessary to calculate the power was found and an actual analysis was not performed. In order to do this the conservation of momentum and Bernoulli's Equation is used in order to determine the power requirement of the UUV. The equations below show the derivation in order to arrive at the power estimate.

$$F_D = \sum_{out} B\dot{m}V - \sum_{in} B\dot{m}V = \dot{m}V_{out} = \rho A V_{out} \quad (14)$$

B=Flux momentum correction factor
$\dot{m}$ =Mass flow rate of water through the propeller

A=Cross sectional area of the circle created by the circular motion of the propeller

From this the above equation, we can solve for V_{out}:

$$V_{out} = \sqrt{\frac{F_D}{\rho A}} \tag{15}$$

Finally Bernoulli's Equation can be used in order to calculate the shaft work needed to propel the UUV at the velocity V_{out}.

$$\dot{m}\left(\frac{P_1}{\rho} + \frac{1}{2}V_{in}{}^2 + gz_1\right) + \dot{W}_{shaft} = \dot{m}\left(\frac{P_2}{\rho} + \frac{1}{2}V_{out}{}^2 + gz_2\right) + \dot{W}_{Turb} + \dot{E}_{mech\ loss} \tag{16}$$

$$W_{shaft} = \dot{m}\frac{V_{out}^2}{2} \tag{17}$$

$\dot{W}_{shaft}$=Shaft Work
$\dot{W}_{Turb}$=Turbine Work
$\dot{E}_{mech\ loss}$=Energy loss due to mechanical inefficiencies
P =Pressure at operating depth
z=Operating depth
g=Gravitational Acceleration

Using the above equations a more accurate power estimate can be obtained. This would be able to provide the fuel cell team with a second iteration power estimate. This would enable more precise sizing of the motors, making the mass and volume budgets better.

Furthermore, using the CFD analysis that was done on the UUV, a possible location for the propeller is found due to the fact that the propeller should be placed in the wake of the flow around the body. This is due to the fact that the slower moving fluid in the wake zone is able to generate more thrust than if the propeller was located in a place where the velocity of the fluid is faster.

V. Conclusions and Recommendations

The fuel cell sub team selected to use a direct borohydride fuel cell with sodium borohydride as the fuel and hydrogen peroxide as the oxidant. The team selected to use a gold catalyst for the oxidant and a 97 wt% gold 3 wt% platinum catalyst for the fuel with a Nafion 961 membrane. Research was performed to determine the optimum fuel cell operating parameters and a detailed design was constructed based on performance found in literature. The team built a prototype fuel cell, which given time for more experiments would likely have seen performance closer to that observed in literature. Much research was done looking into problems with sodium transport across the membrane, but no good solution was found. One potential solution would be to use an anion exchange membrane, but at present no working anion exchange membranes exist. Further work to be done would include experimenting with the prototype under different operating conditions. The existing detailed design could be refined with better estimations, and an entirely new detailed design should be made using the prototype performance. Now that a preliminary detailed design exists it would also be worthwhile to try and get a cost estimate.

In order to produce an accurate estimate of the power needed in to propel the submarine through the ocean an accurate drag estimate has to be obtained. In order to do this, a model similar in shape and material to the final product needs to be produced and tested in a water tunnel (which is unavailable at IIT). Once accurate estimates of the power are obtained, it will be possible to provide the fuel cell team with precise power requirement which they can use in order to design the fuel cells to meet these power requirements. One alternative to using a water tunnel, is to use computational fluid dynamics or CFD in order to estimate the drag coefficient for our UUV. However, the resources needed to do so at IIT are hard to find and require a fair amount of computational time. Furthermore, more analysis and design of the ballast tanks, the control system, and propeller design is required. This can be done next year if this IPRO is continued.

VI. Appendices

Appendix 1: Team Roster

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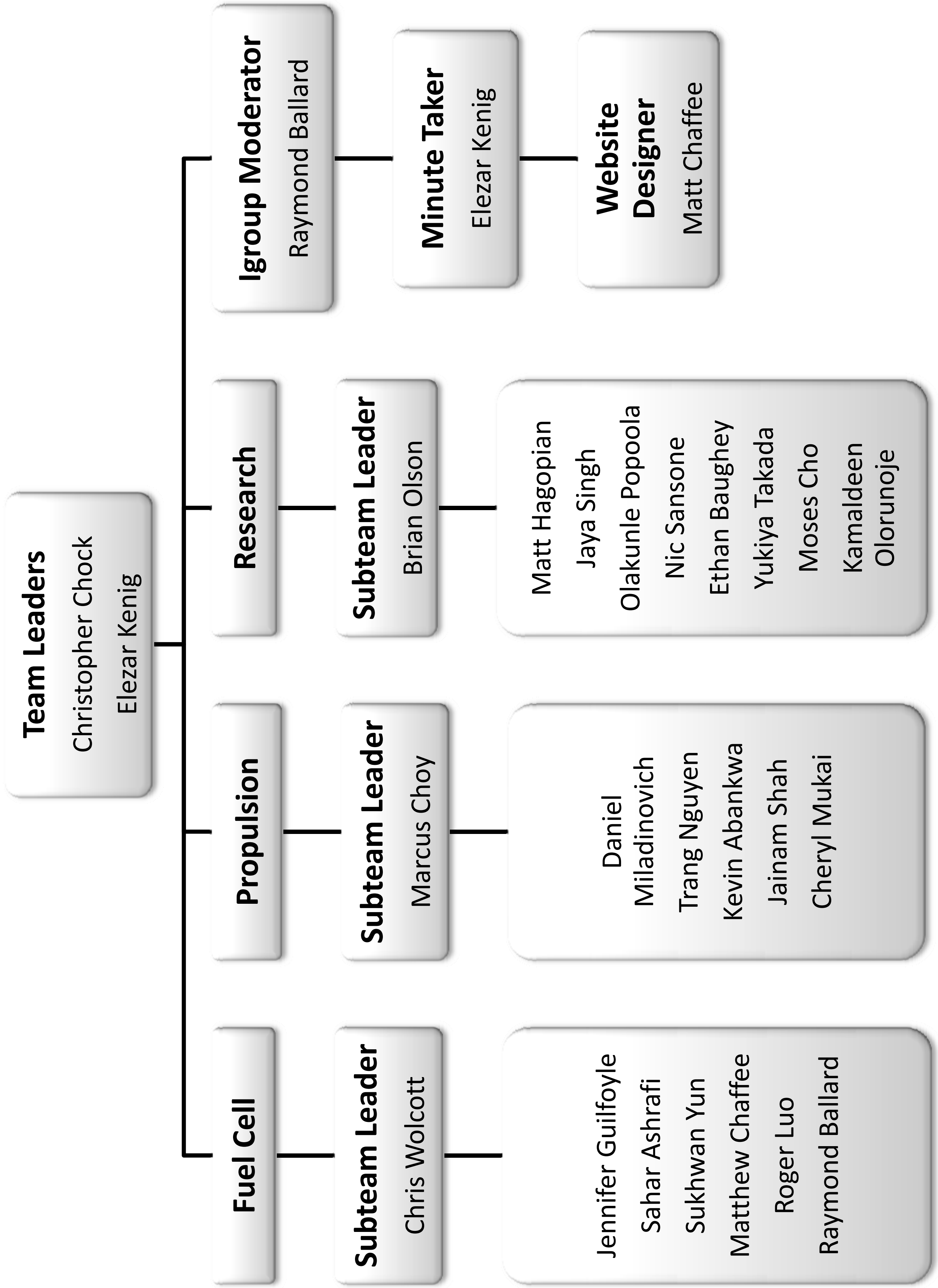
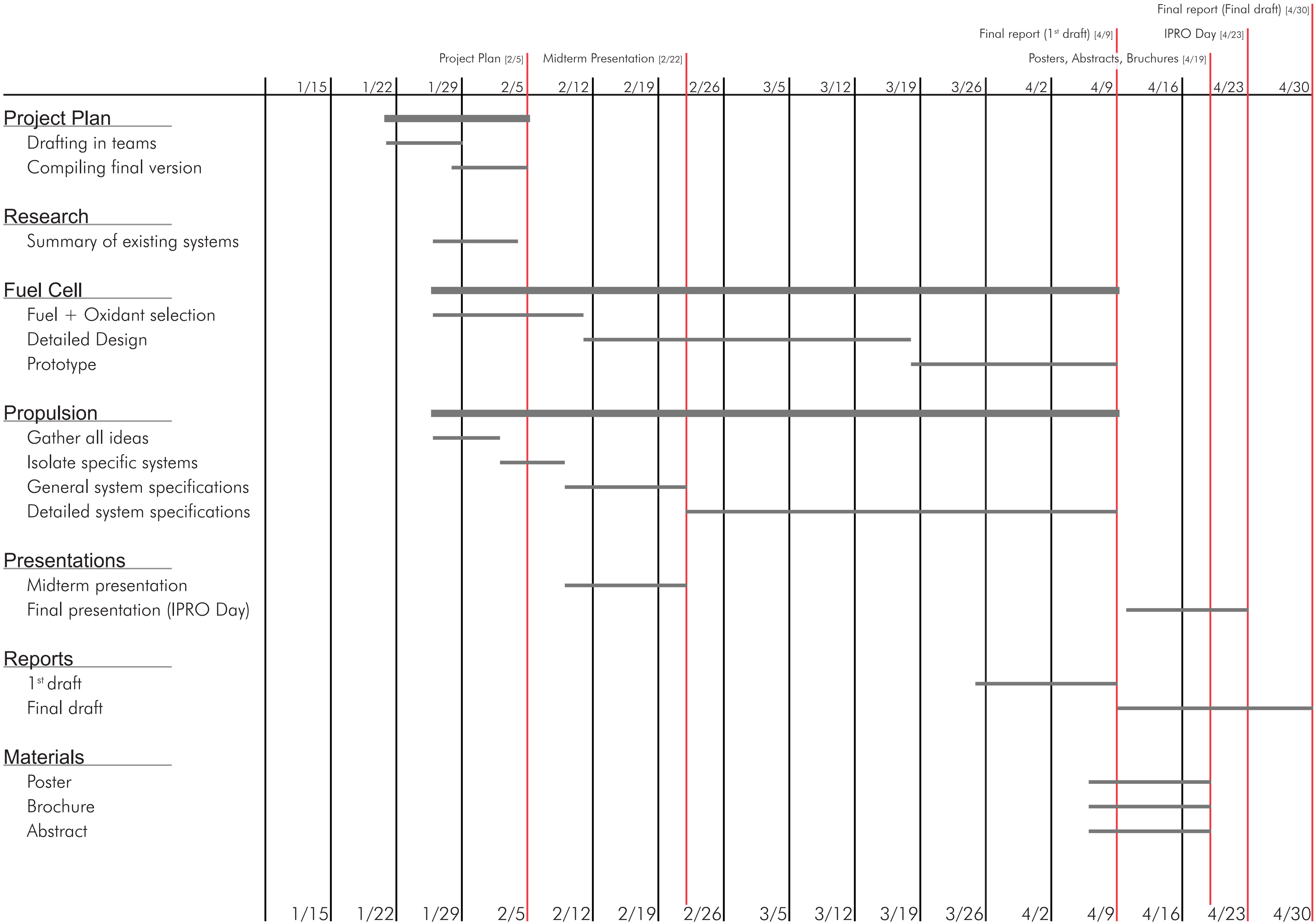
Appendix 2: Team Structure



Appendix 3: Gantt Chart

IPRO 349: Fuel cells for Undersea Vehicles



Appendix 4: Budget

Activity	Cost	Description
Experimentation Fuel Cell Kits	$350	Two fuel cell kits to be purchased to simulate the performance of our fuel cell
Experimentation Fuel, Oxidant, Membrane, and Catalysts	$600	$215 for borohydride $50 for hydrogen peroxide $150 for membrane materials $150 for purchase of 2 catalyst $35 DC motor kit These items will be used in conjunction with the fuel cell kit for research and simulation purposes
Book	$45	Book on design of Submarines to help with designing the UUV
TOTAL	$995	

Appendix 5: Sources

FC1. Direct liquid-feed fuel cells: Thermodynamic and environmental concerns, Demerci U. B., Journal of Power Sources, 169, (2007) 239–246.

FC2. NaBH4/H2O2 fuel cells for air independent power systems, Luo N. et al, Journal of Power Sources 185, (2008), 685–690.

FC3. A Comprehensive Review of Direct Borohydride Fuel Cells, Ma J., Choudhurt N. A., Sahai Y., Renewable and Sustainable Energy Reviews, 14, 2010, 183-19*.

FC4. A Direct Borohydride/ Hydrogen Peroxide Fuel Cell with Reduced Alkali Crossover, Raman R. K., Shulka A. K., **Fuel Cells**, 2007, 3, 225-231.

FC5. A Self-Supported Direct Borohydride-Hydrogen Peroxide Fuel Cell System, Shulka A.K. et al, **Energies,** 2009, 2, 190-201.